Cooperative Gust Sensing and Suppression for Aircraft Formation Flight (NNX14AF55A)

NASA Aeronautics Research Mission Directorate (ARMD)

2015 LEARN Technical Seminar

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Overview

- Motivations and Objectives
- Project Team
- Phase I Research and Lessons Learned
- Phase II Research
- Next Step
- Distribution/Dissemination

Impact & Challenges

- Autonomous close formation flight is an enabling technology for many future concepts of operations involving both manned and unmanned aircraft
- Its potential benefits include energy saving and improved air traffic coordination within high density airspace
- The inherent risks associated with close-proximity flights have hindered breakthrough developments in this field
- With the follower aircraft constantly flying in the leader's wake, several technical challenges remain unsolved

Problems & Innovations

Research Problems

- How to actively suppress the ambient and wake-induced turbulences so that the follower will fly safely and smoothly behind the leader
- How to mitigate the risk of unexpected wake encounters, e.g., the transition phase of the formation flight

Innovation

- A cooperative approach taking advantage of the spatial distribution of a group of aircraft flying in formation and information exchanges among aircraft
- For example, through the use of ambient wind information sensed by the leader and a prediction of the leader's wake propagation pattern, a follower can dynamically adjust its position for energy saving, wake turbulence minimization, and/or collision avoidance

Objectives

Overall Project

- Develop and experimentally validate a cooperative strategy for gust sensing and suppression within a close formation flight setting

Phase I

- Proof of concept demonstrations of close formation flight and gust/wake estimation algorithms

Phase II

- Refinement of the wake models, gust/wake estimation algorithms, and gust suppression control schemes developed during Phase I, leading to performing in-flight cooperative gust sensing and suppression control experiments

Project Team (Phase II)

NASA Program Manager:	Datta, Koushik (ARC)
NASA Technical Officer:	Curtis E. Hanson (AFRC)
Principal Investigator:	Yu Gu (WVU)
Co-Investigator:	Marcello Napolitano (WVU) Haiyang Chao (KU) Zhongquan Charlie Zheng (KU)
Collaborator:	Jason Gross (WVU)
Graduate Students:	Caleb Rice (WVU, graduated) Jared Strader (WVU) Tanmay Mandal (WVU) Anpeng He (KU) Pengzhi Tian (KU)
Undergraduate Students:	Scott Harper (WVU) Alex Gray (WVU, graduated) Anthony Donzella (WVU) Matthew Gramlich (WVU) Zorig Bat (KU)

Phase I Achievement

Cooperative Gust Sensing and Prediction

- An Unscented Kalman Filter (UKF) for real-time wind estimates

Active Gust Suppression Control

- A preliminary set of gust suppression control laws

Flight Simulation and Validation

- A formation flight simulator, which includes ambient and wake induced wind and gust models
- More than 40 flight tests were performed, including 8 close formation flight experiments

Lessons Learned

- The diameter of the wake vortices is fairly small. For our testbed aircraft, the core radius of the wake after roll-up is only about 9 cm with a maximum tangential velocity at about 1.5 m/s. The radius for 1.0 m/s tangential speed is approximately 25 cm. This brings up two major challenges in sensing and control:

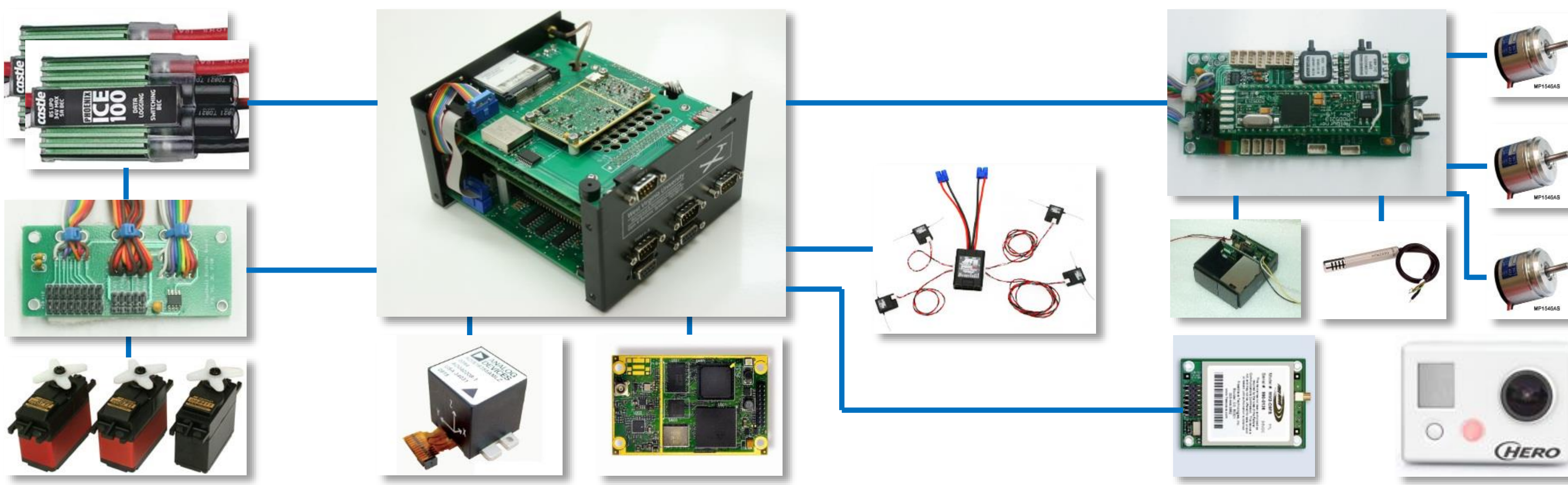
  1. The follower needs to be precisely controlled, ideally with an accuracy of ± 0.1 wingspan, such that the follower is able to be placed at a desirable location in the wake
  2. It is very challenging to sense the vortex from the follower. Multiple spatially distributed sensors are needed

- For a small sub-scale aircraft, the wake-induced wind speed can be on the same order of magnitude as the ambient wind speed. Therefore, the vortices will quickly dissipate or be convected away in the ambient wind. This makes it even more challenging for vortex detection and gust estimation

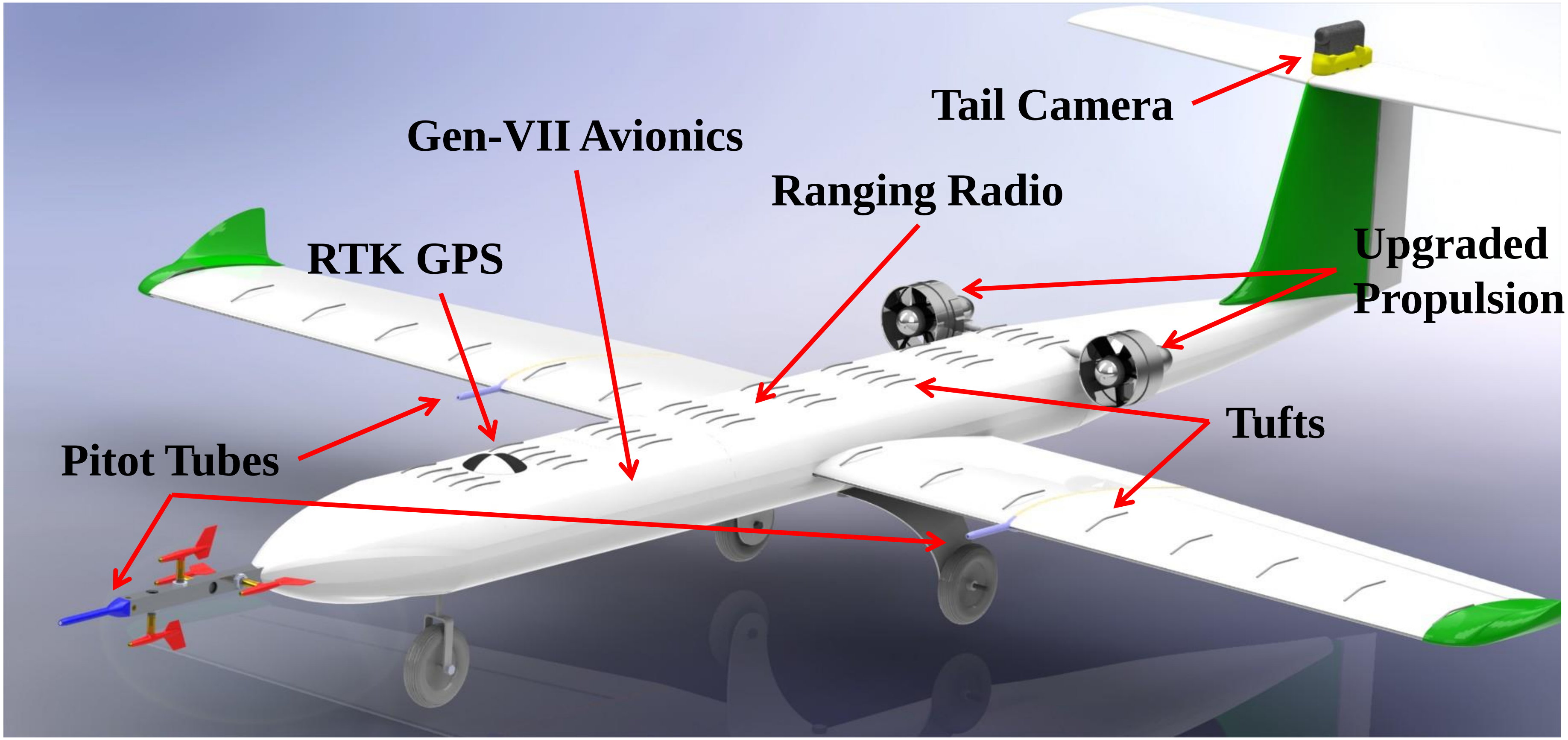
Phase II Activities

- Achieve high-quality formation flight in terms of both navigation and control performance
- Allow spatially distributed sensing of the airflow around the test bed aircraft
- Improved wake Identification from UAV formation flight data
- Detailed wake encounter model development
- Real-time testing of cooperative wake sensing and gust suppression algorithms

Phastball Aircraft During Phase I



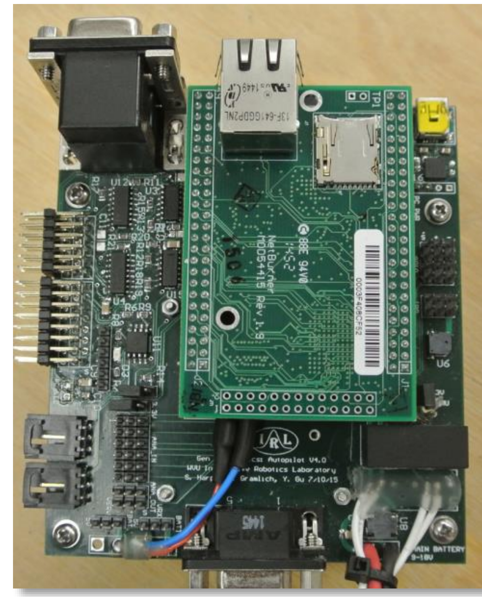
Hardware Upgrades for Phase II



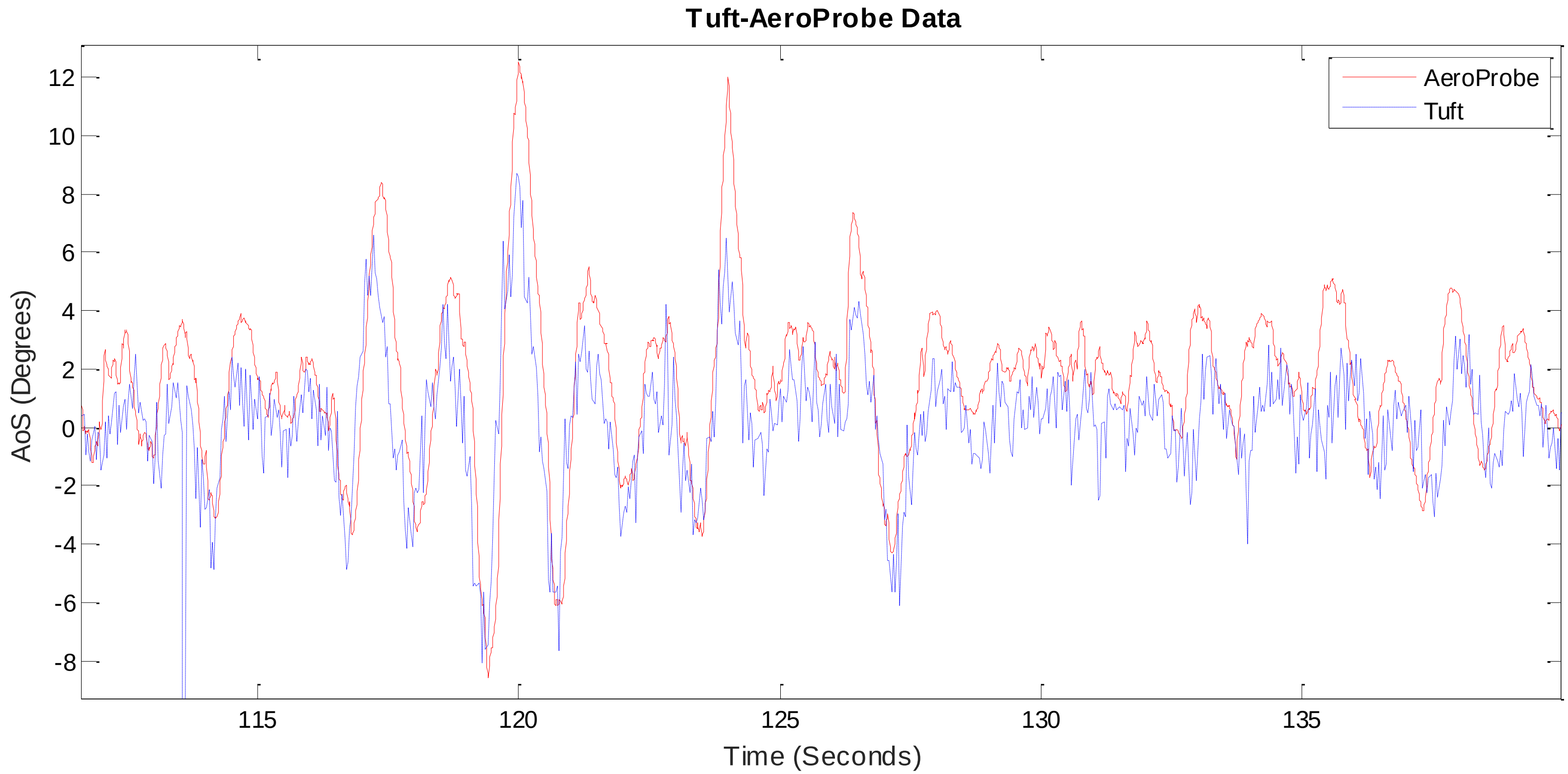
- Improvements are made in terms of navigation, flight control, propulsion, communication, computation, flow-visualization, and wake sensing

Gen-VII Avionics

- Custom avionics designed to support high-precision formation flight
- Improved navigation sensor (e.g. IMU, and RTK GPS) performance
- Expanded I/O connectivity to accommodate additional sensors (e.g. two additional 5-hole pitot tubes)
- Multiple ways of vehicle to vehicle and vehicle to ground communication
- High servo control update rate (~400Hz)
- Enhanced computational power



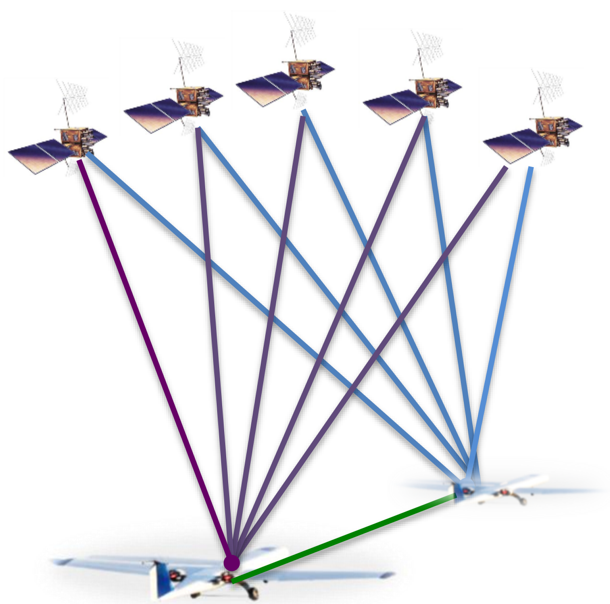
Computer Vision Tuft Result

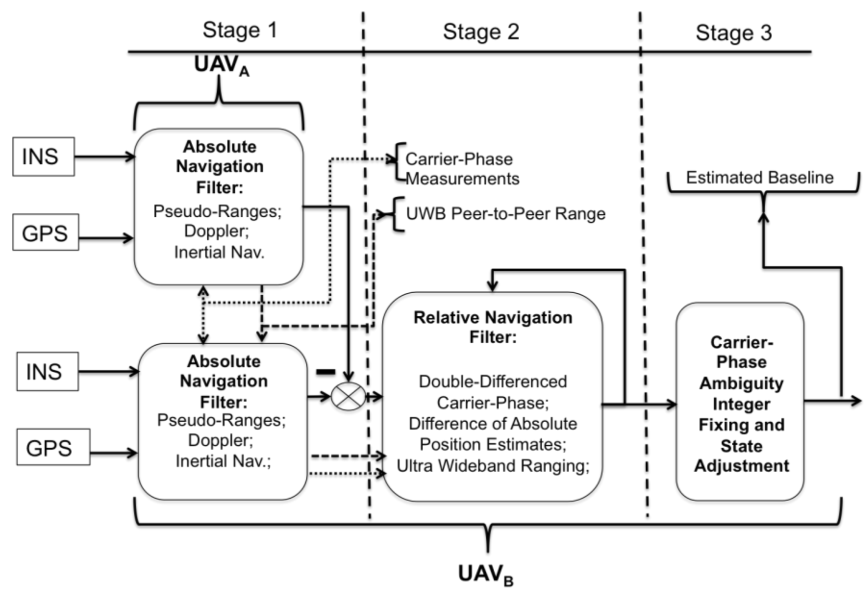


Tufts During Root Stall and Recovery

Precision Navigation

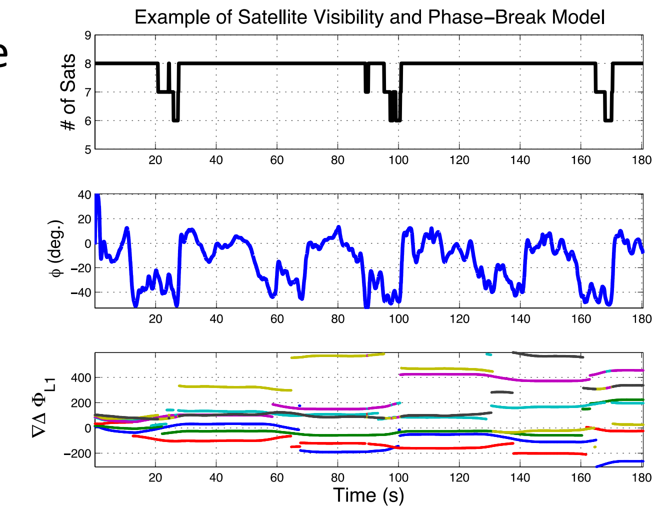
- The formation keeping error includes both the control error and navigation error
- The fast dynamics of small UAVs (e.g. Phastball) pose many challenges to precision navigation due to an increase in the occurrence of phase breaks/cycle slips
- Peer-to-peer radio ranging systems in the UAVs have been introduced in order to increase the robustness of tightly-coupled DGPS/INS

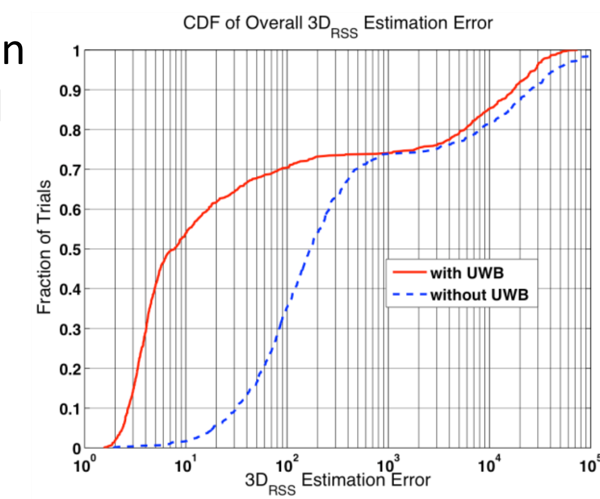




Tightly-Coupled GPS/INS/TW-TOF Ranging Radio for Relative Navigation

- The key is resolving the integer ambiguity of the double-difference carrier-phase measurements between the UAVs
- As the UAVs roll, satellite loss of lock occurs leading to new integer ambiguities (example shown top-right)
- Our architecture increases the percentage of epochs with successful integer ambiguity resolution and also improves relative navigation accuracy when ambiguities cannot be resolved (bottom-right is the result of a 1000 Monte Carlo trials)





Gross, Jason N., Yu Gu, and Matthew B. Rhudy. "Robust UAV Relative Navigation With DGPS, INS, and Peer-to-Peer Radio Ranging.", IEEE Transactions on Automation Science and Engineering, 2015. doi: 10.1109/TASE.2014.2383357

Wake Sensing and Suppression

Wake Estimation

- Refine the wake model for ‘Phastball’ aircraft starting from Bumahm-Hallock wake vortex model and Sarpkaya decaying model
- Investigate the interactions between the ambient wind and wake-induced vortices

Wake Encounter Model

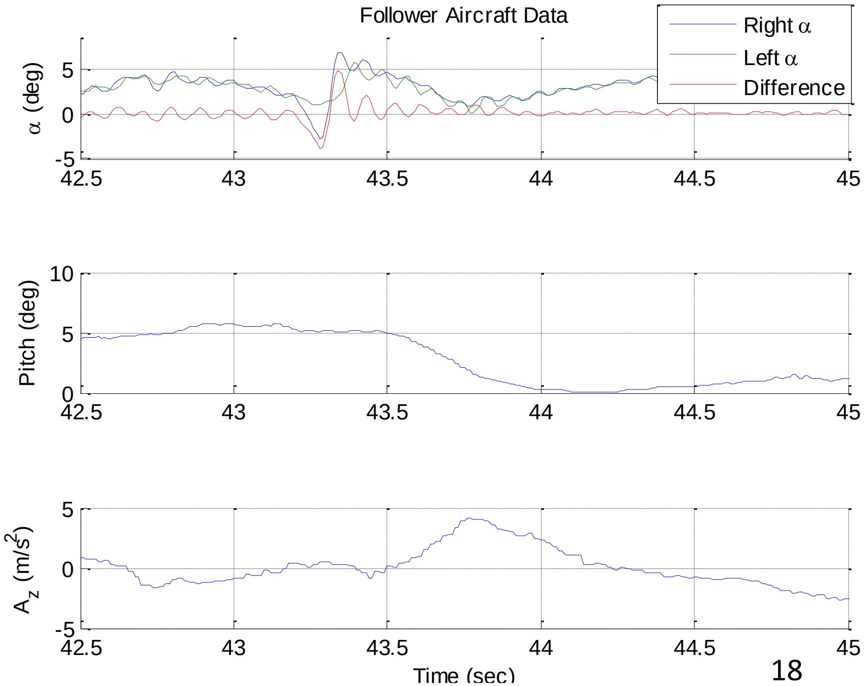
- Simulation of wake induced forces and moments using lifting-line theory and panel method
- Quantify the aerodynamic benefits of a dynamic ‘sweet spot’ following close formation flight (simulation)

Gust Alleviation Control

- Cooperative gust suppression control in close formation flights under different gust conditions

Wake Sensing Flights (Phase I)

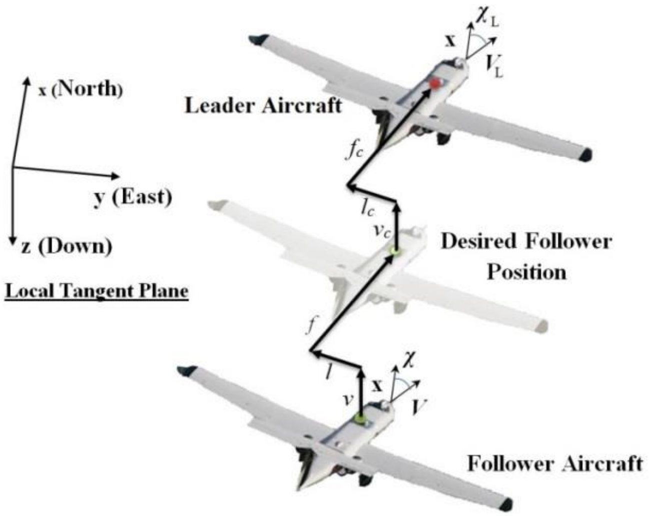
- Flight data were collected with a pitot tube, two alpha vanes (25cm apart) and one beta vane on the aircraft
- Weather station collects wind speed and direction data on the ground
- The air data system was calibrated on a calm day



Wake Encounter Identification

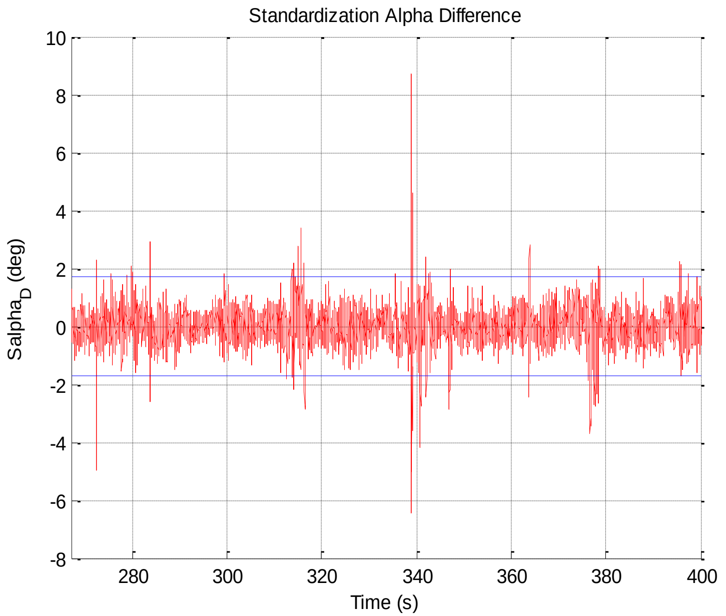
- Objective: Wake Encounter during Wings-Level Straight Flight
- Leader – Follower Formation Flight with Adjustable Offsets
  - Longitudinal Offset: (12 ~ 50) m, or (5 ~ 20b)
  - Lateral Offset: (-12 ~ 12) m, or (-5 ~ 5b)
  - Vertical Offset: (-12 ~ 12) m, or (-5 ~ 5b)
- Summary of 10 Close Formation Flight

Flight No	Desired Geometry Range (m)	Separation Adjustability	Corrections	Wake Encounter Detected
1/2/3	(50/40/30, 0, 0)	No	N/A	No
4	(24±12, ±12, ±12)	Yes	N/A	No
5	(12, 0, 0)	No	N/A	No
6	(24±12, ±12, ±12)	Yes	N/A	No
7	(12, -1.2, 0)	No	Vertical bias added	Yes
8	(12, -1.2, 0)	No	Vertical bias added	Yes
9	(24±12, ±12, ±12)	Yes	N/A	No
10	(12, -1.2, 0)	No	Vertical bias added	Yes



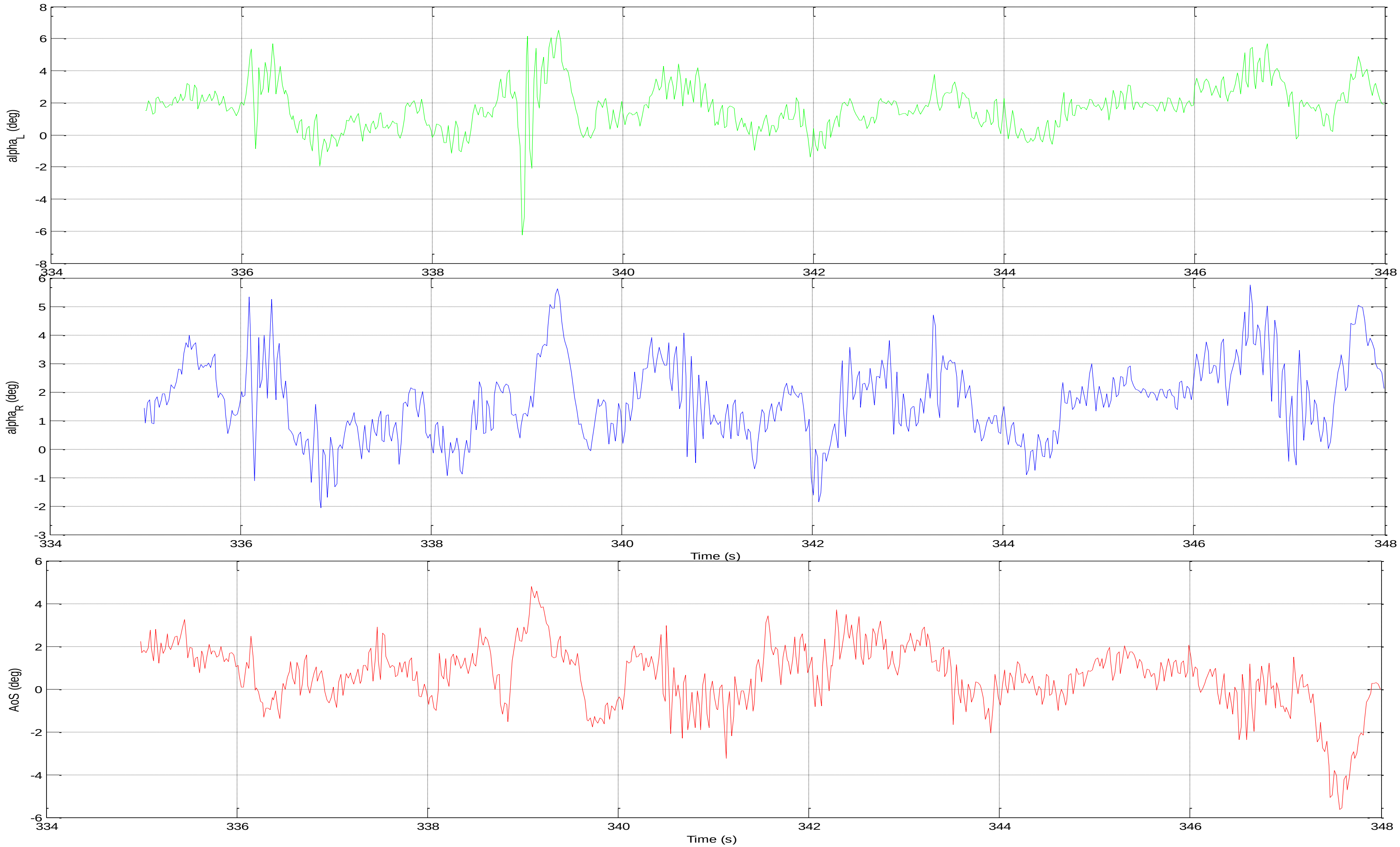
Wake Encounter Identification (Cont.)

- Wake Measurements:
  - Fuselage mounted AOA/AOS sensors
  - Accelerometer, gyros
- Major Indicator for Phastball Formation Flight:
  - The difference between the left and right AOA sensors (fuselage-mounted 25cm apart)
  - Wake encounter happened when the difference went over 3 sigma range
- Wake Encounter Indications for Flight No. 7 (Straight-Legs):
  - Left AOA - right AOA > 3σ (1.7142 deg.)
  - Abrupt movements of AOA (> 5 deg.)
  - Abrupt movements of AOS (> 5 deg.)
  - Abrupt rolling after the wake encounter
  - Consequent vertical motions observed from accelerometer measurements (~ -1.6 G)



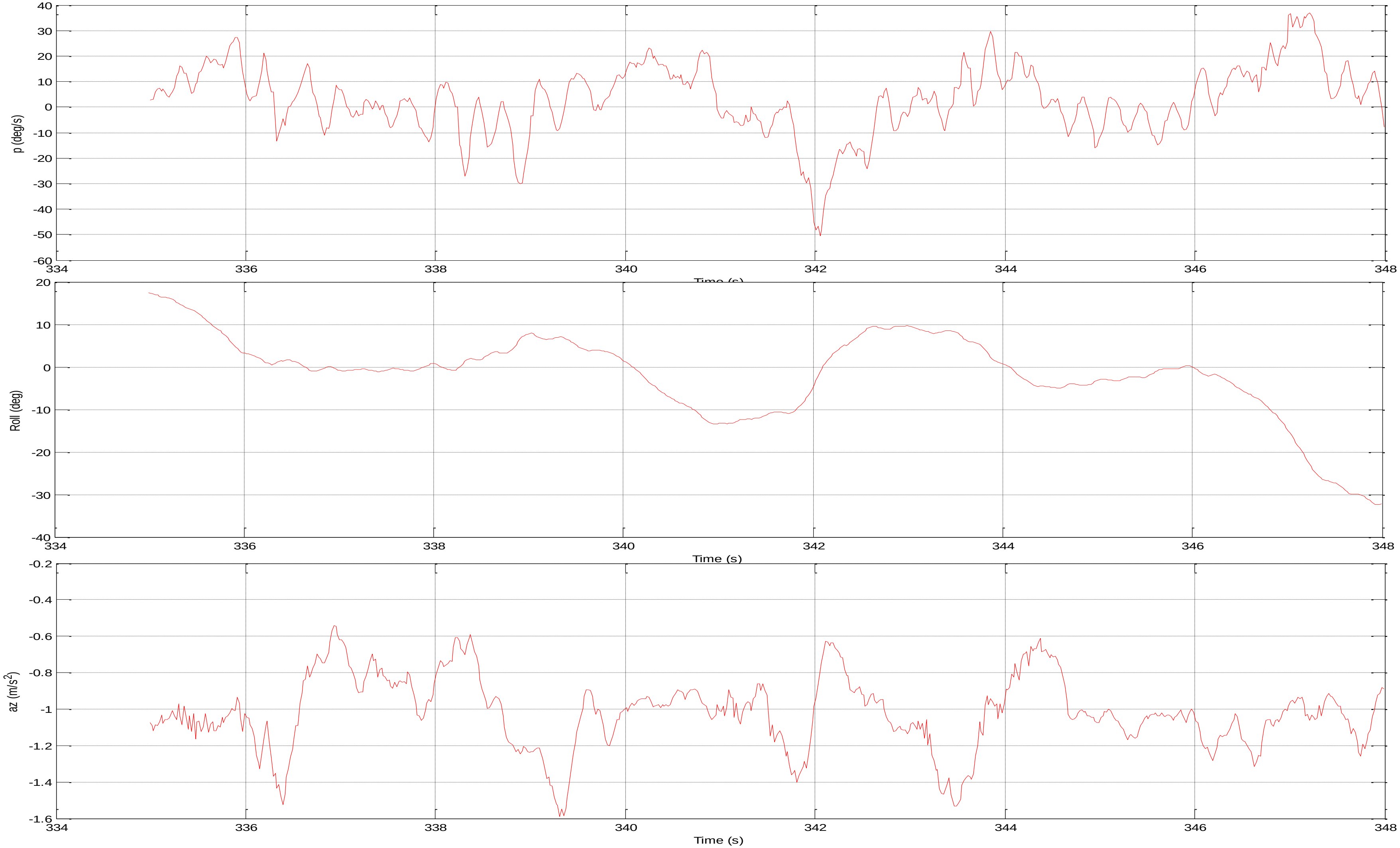
Wake Encounter Identification (Cont.)

- Sample Wake Encounter Data (Flt No. 7) - $\alpha_L/\alpha_R/\beta$



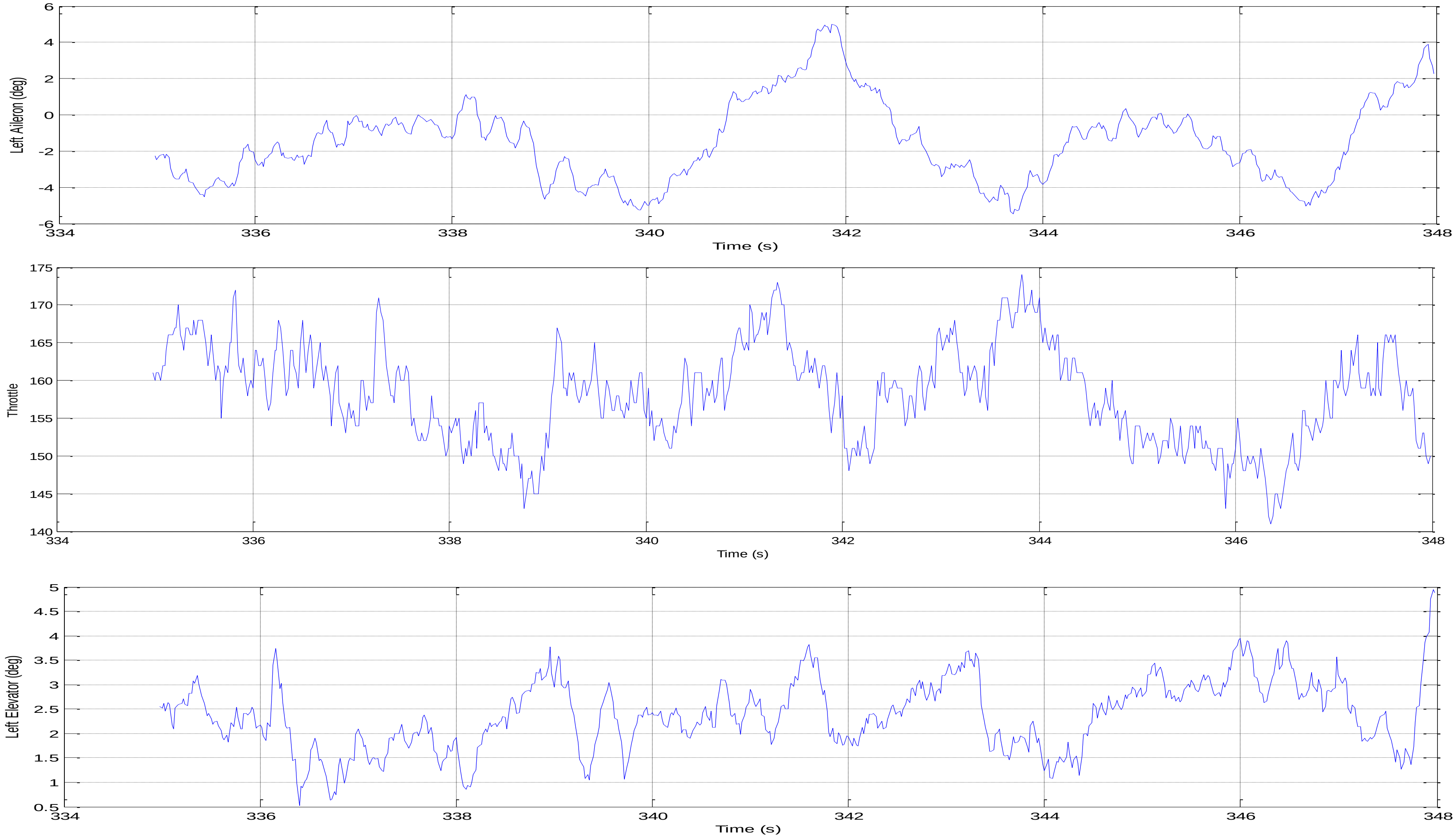
Wake Encounter Identification (Cont.)

- Sample Wake Encounter Data (Flt No. 7) – p/roll/az



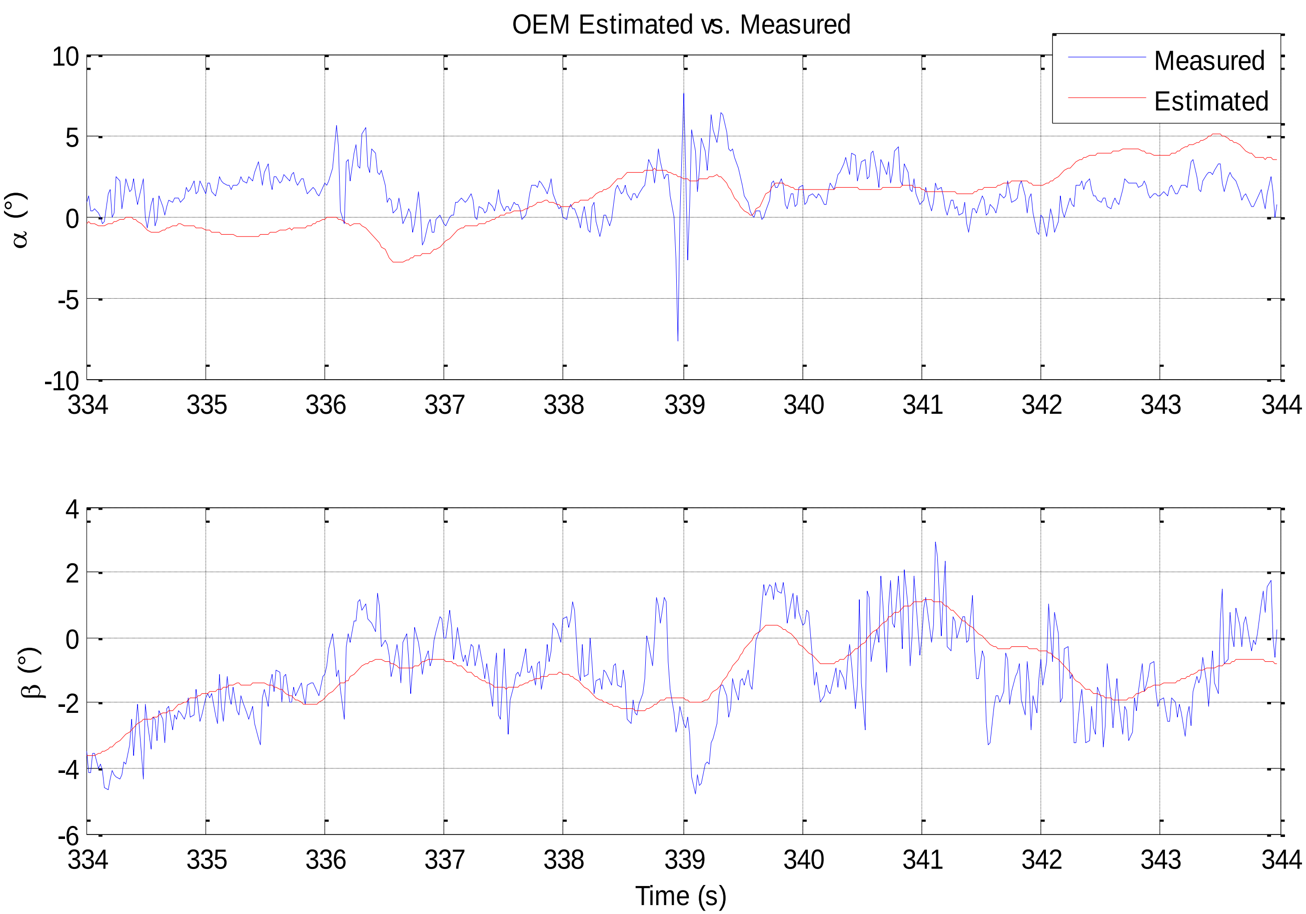
Wake Encounter Identification (Cont.)

- Sample Wake Encounter Data (Flt No. 7) – Aileron/Throttle/Elevator



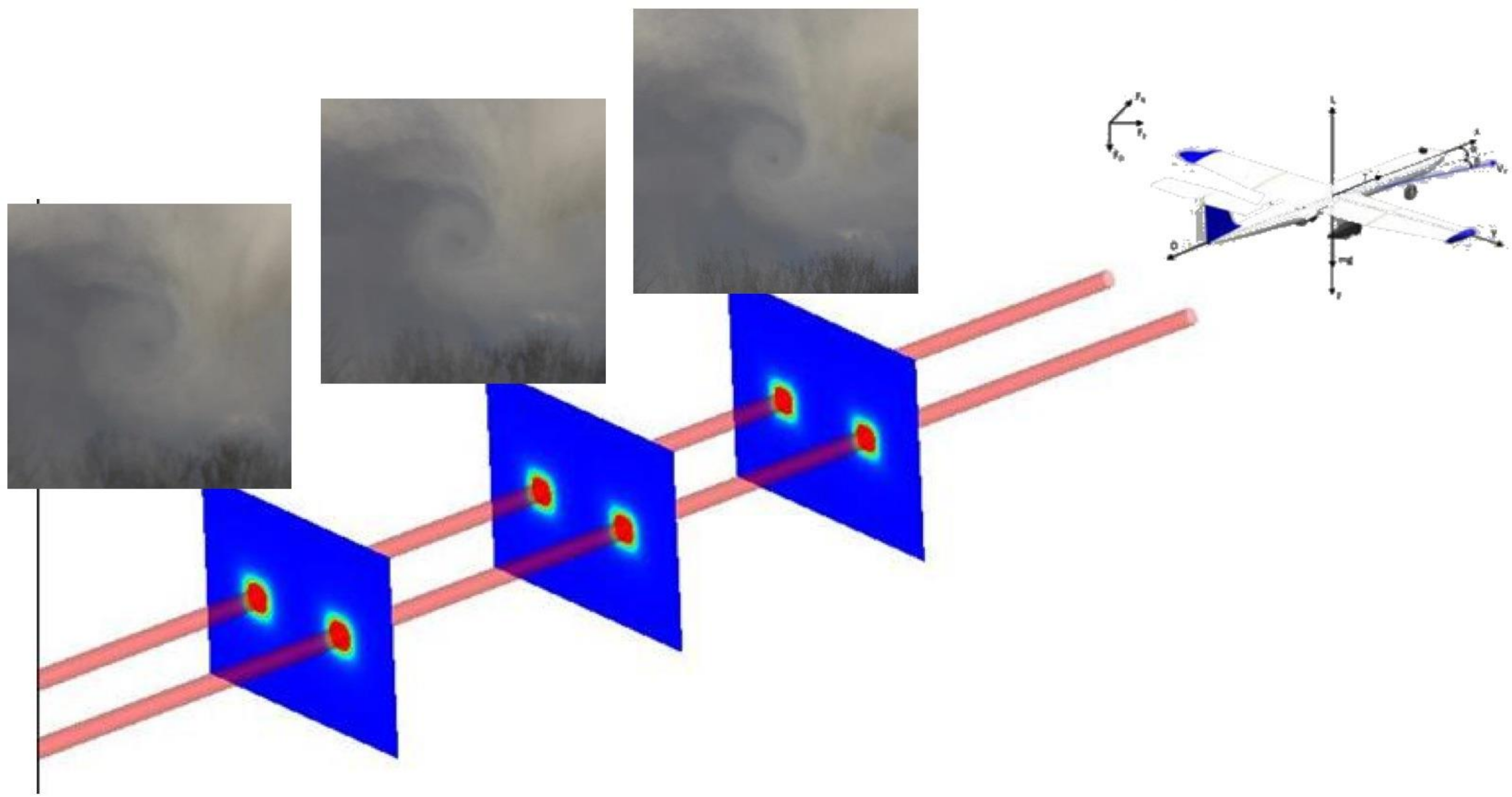
Wake Model Identification

- Wake Models can be estimated from the difference between measured AOA and inertial AOA estimated from p/q/r/ax/ay/az (output error minimization).



Wake Encounter Aerodynamic Modeling

- Currently working on the estimation of wake model parameters
- Hallock-Burnham vortex: $v_\theta(r) = \frac{\Gamma_i}{2\pi r}\frac{r^2}{r^2+{r_c}^2}$
- Sarpkaya wake delay model: $\Gamma_i = \Gamma_0 \exp\left(\frac{-Cd(\varepsilon\Gamma_0)^{0.25}}{1.2727V_0 b_0}\right)$

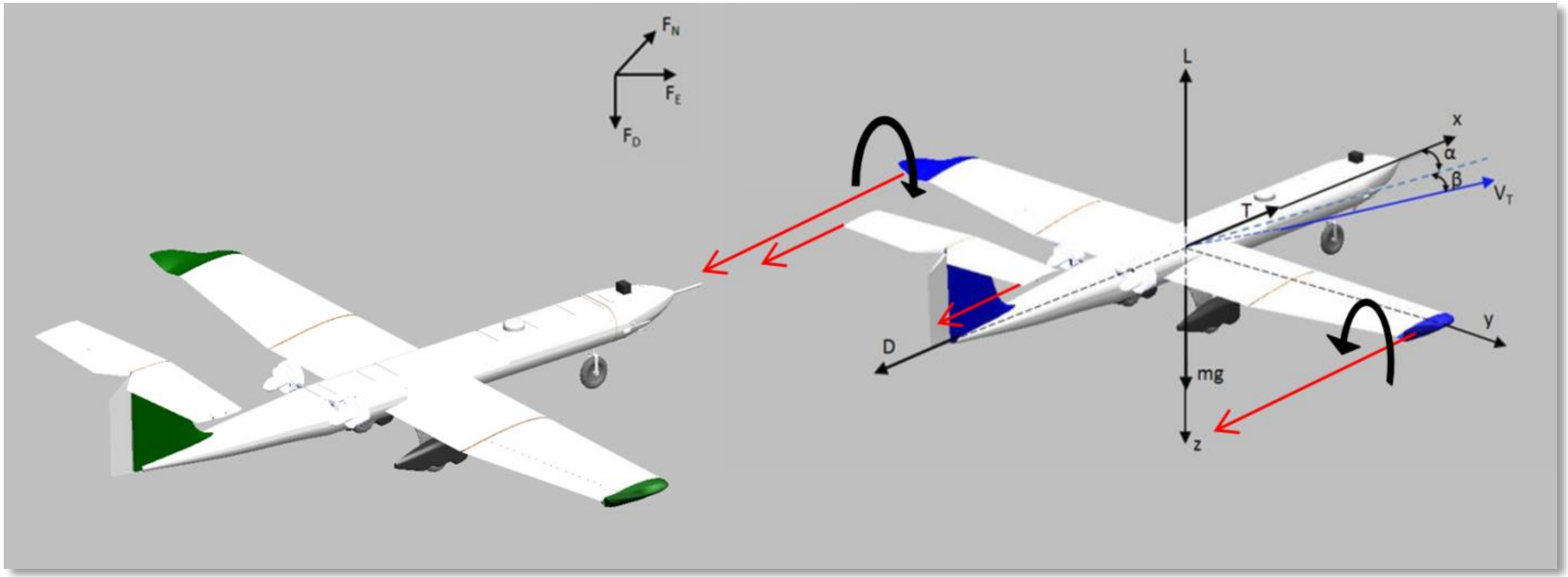


Wake vortices of Phastball UAV after roll-up (Core radius: 0.09 m, initial circulation: 1.72 m²/s)

Wake Encounter Aerodynamic Models

Methods

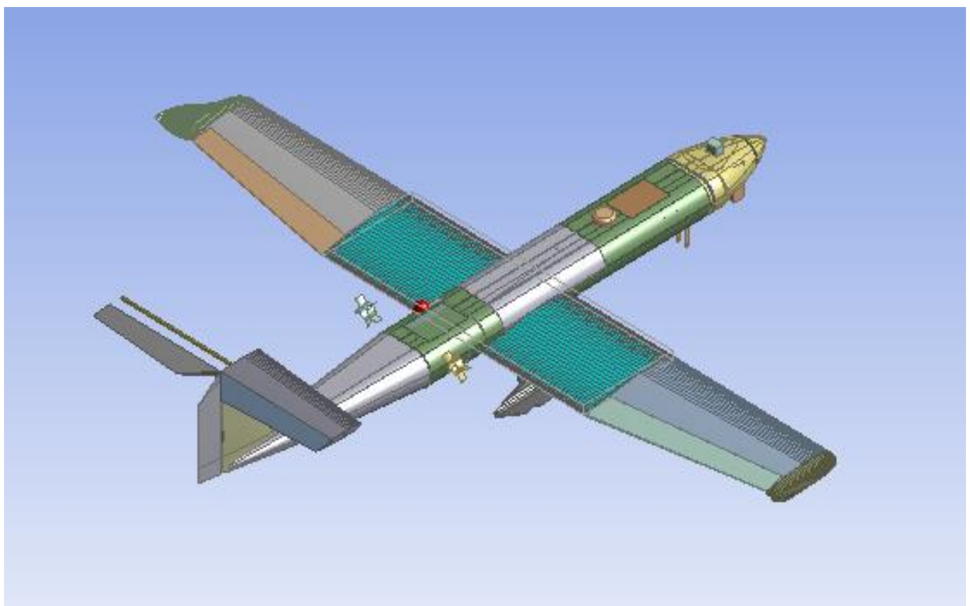
- Strip theory
- Vortex lattice method
- Compared and validated with the flight measurements

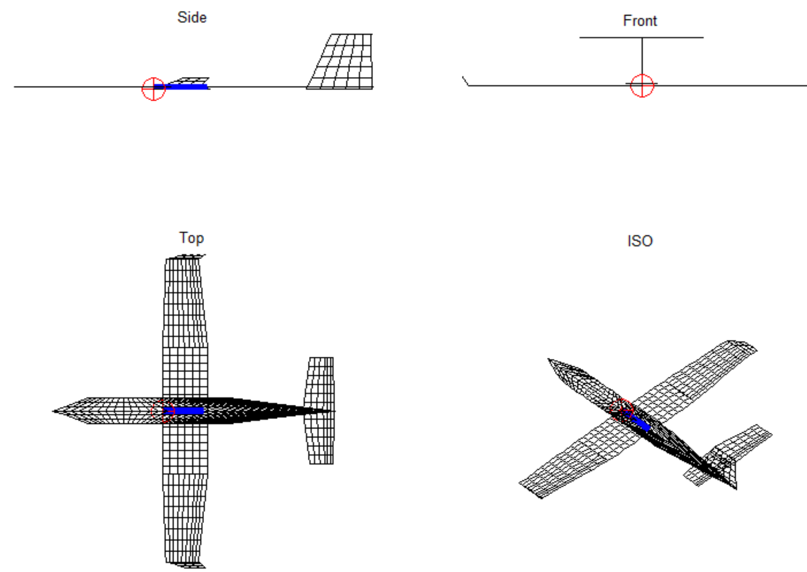


Wake Encounter Aerodynamic Models

Vortex Lattice Method

- NACA 2410 for main wing
- NACA 0009 for tail
- T-tail configuration

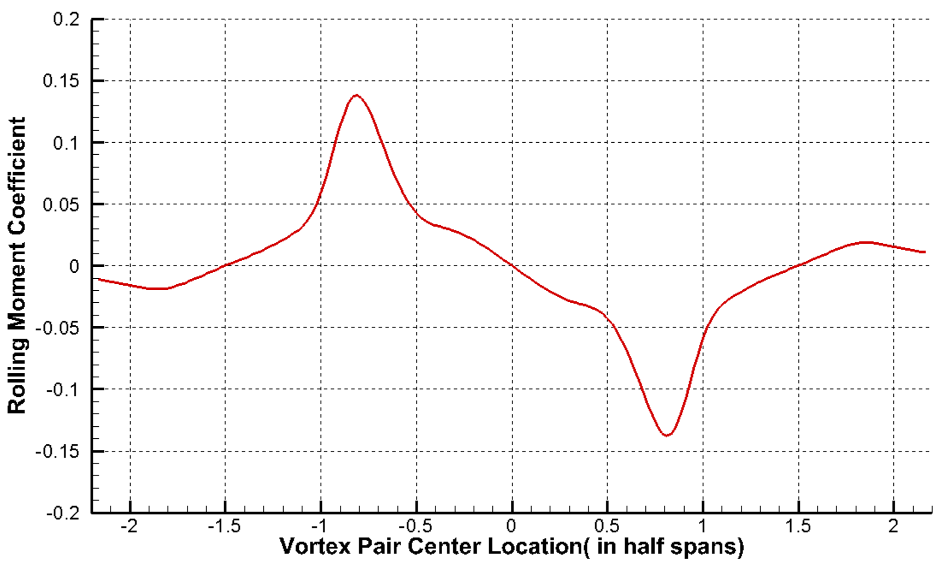




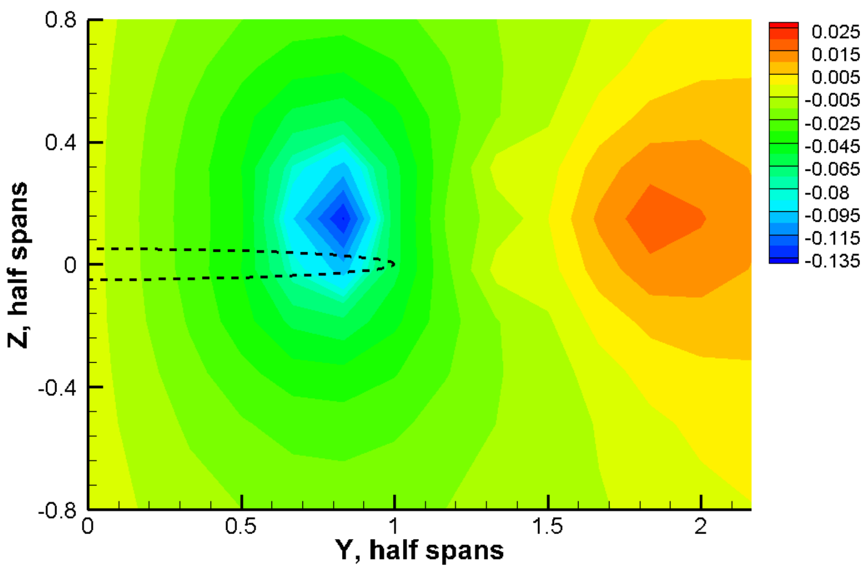
WVU Phastball Model and the mesh build in Tornado

Wake Encounter Aerodynamic Models

- Distance of the two UAVs 12 m, V= 30 m/s, AOA = 2 deg., Γ= 5.25 m2/s, Δh = 0.179 m, Wingspan 2.4m
- At Y = 0, the center of the fuselage, the induced rolling moment coefficient is 0
- The greatest rolling moment occurs when the center of vortex pair is at Y = 0.8 half span
- Considering the vortex descending, the peak value in the contour is shifted vertically



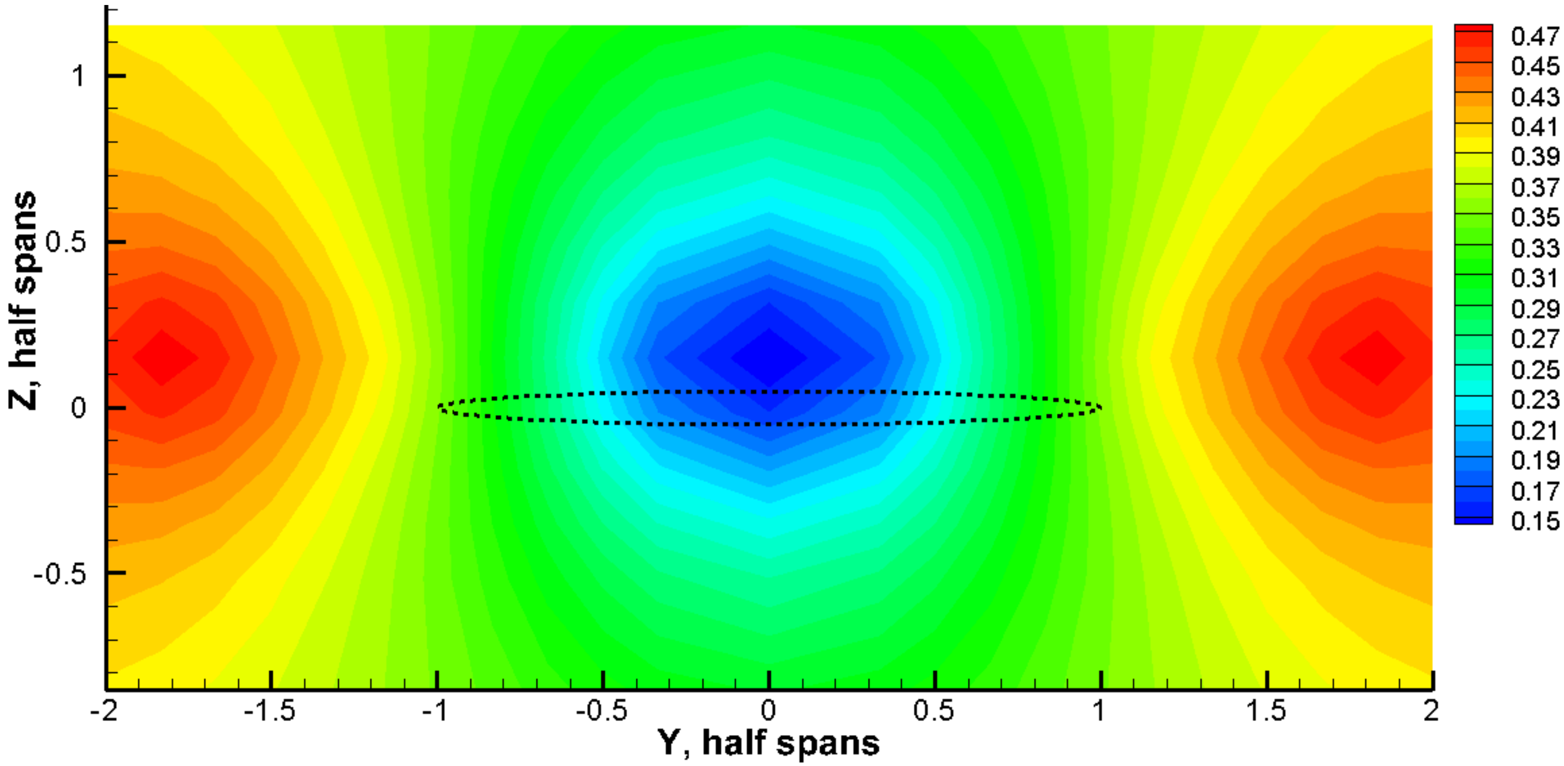
Vortex pair locations relative to the following UAV fuselage (Z=0)



Rolling moment coefficient field with the leader locations relative to follower fuselage

Wake Encounter Aerodynamic Models

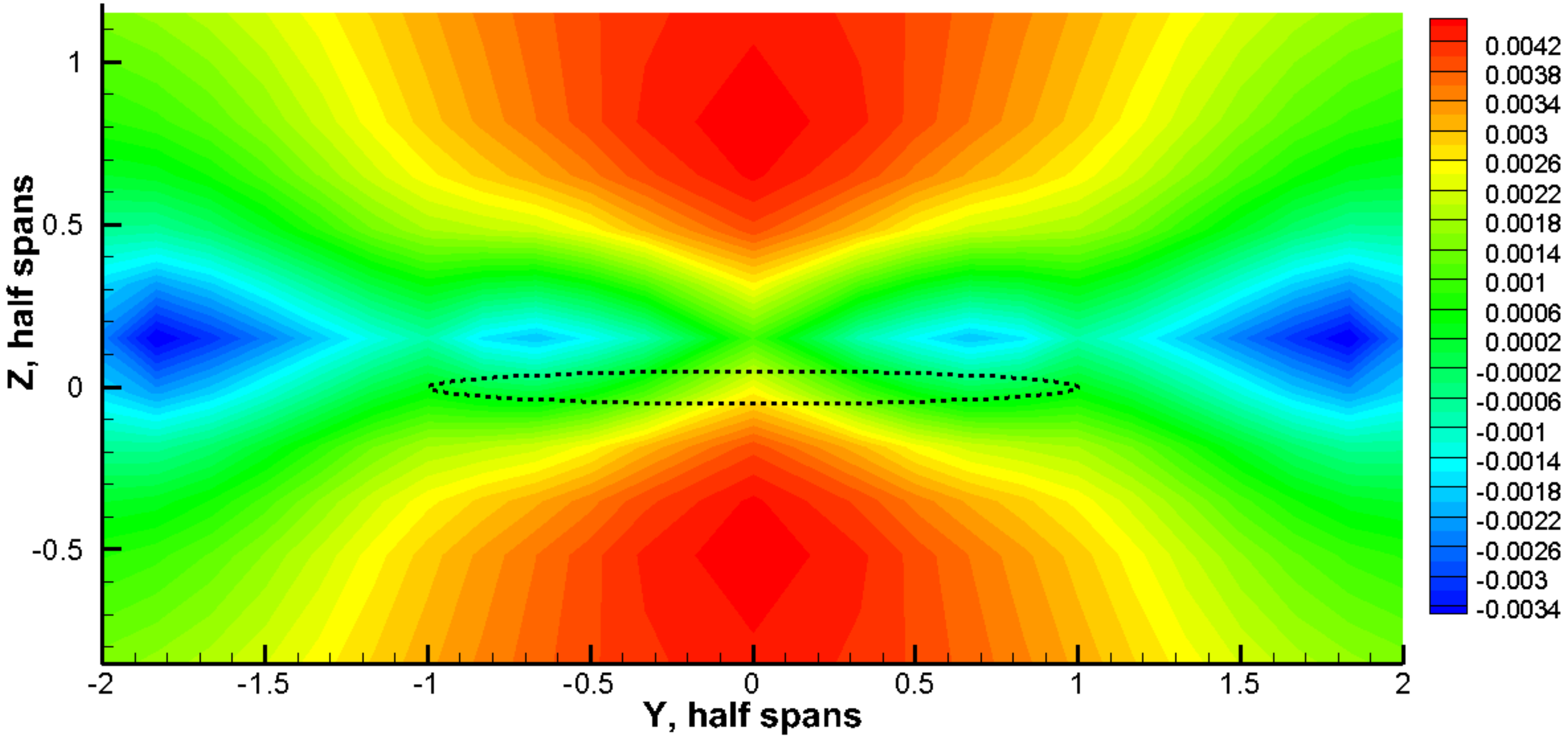
➢ The follower has the greatest lift coefficient when the leader is at (1.8, 0.15), and (-1.8, 0.15) relative to the follower



Cl field with the leader location relative to follower

Wake Encounter Aerodynamic Models

- The follower has the greatest negative drag coefficient when the leader is at (-1.8, 0.15) and (1.8, 0.15)



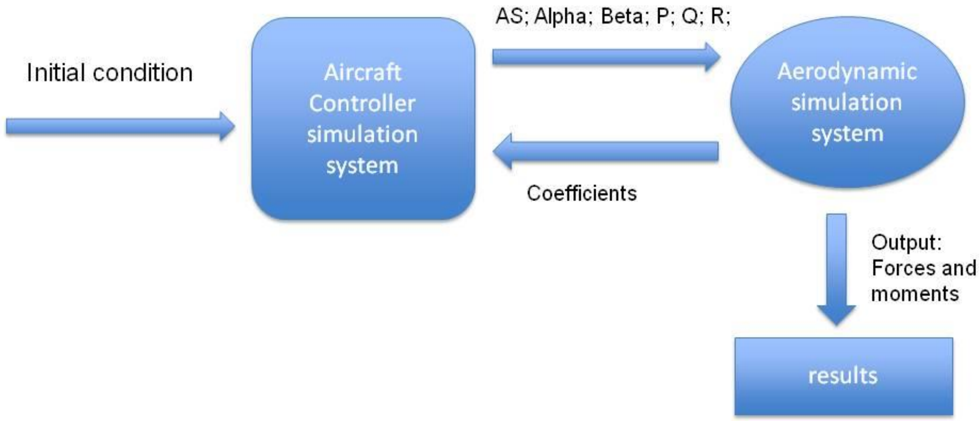
Cd field with the leader location relative to the follower

Wake Encounter Aerodynamic Simulation

KU-Wake Encounter Aerodynamics Simulation (KU-WEAS) Platform

- Flight dynamic simulation based from MATLAB FDC toolbox
- Aerodynamic calculation based from vortex lattice methods or other aerodynamic computation
- Supports WVU Phastball UAS
- Easy adaptation to other UAS or manned aircraft

Formation Flight Simulation



Cooperative Gust Suppression

- A feed-forward link was added to the inner loop flight controller using the gust/wake estimation (Phase I)
- The gust alleviation controller to be develop during Phase II will utilize two complementary strategies:
    1. Prepare the aircraft for an incoming gust through deflections of the aircraft surfaces
    2. Actively fine tune the formation geometry to stay in the favorable portion of the wake
- We will be focusing on longitudinal dynamics
- The gust conditions will include single and multiple frequency contents, and other types of atmospheric turbulence spectra
- Extensive simulation and flight testing experiments will be performed to evaluate the controller performance

Next Steps

- Continued precision formation flight experiments for wake data collection
- Validation of the wake encounter models with flight data
- Fully coupled flight dynamic-aerodynamic simulation to investigate wake effect
- Refinement and simulation validation of cooperative wake sensing and suppression algorithms
- Perform real-time wake estimation and gust suppression experiments
- Looking for additional research topics related to close and precision formation flight

Distribution/Dissemination

- Rhudy, M., Fravolini, M.L., Gu, Y., Napolitano, M., Gururajan, S., and Chao H., "Aircraft Model Independent Airspeed Estimation without Pitot Tube Measurements," Accepted, to appear in IEEE Transactions on Aerospace and Electronic Systems, 2015
- Gross, J., Gu, Y., and Rhudy, M., "Robust UAV Relative Navigation with DGPS, INS, and Peer-to-Peer Radio Ranging," Accepted, to appear in IEEE Transactions on Automation Science and Engineering, 2015
- Tian, P. , Chao, H., Gu, Y. , and Hagerott, S., "UAV Flight Test Evaluation of Fusion Algorithms for Estimation of Angle of Attack and Sideslip Angle", AIAA Guidance, Navigation, and Control Conference, to appear, 2016
- Chao, H., Gu, Y., Tian, P., Zheng, C., and Napolitano, M., "Wake Vortex Detection with UAV Close Formation Flight", AIAA Atmospheric Flight Mechanics Conference, 2015
- He, A. and Zheng, C., "Simulation of Wake Encounter for Aircraft Close Formation Operations", AIAA Atmospheric Flight Mechanics Conference, 2015

Thank You!